Competency 1.4 **Radiation protection personnel shall demonstrate a working level knowledge of the biological effects of radiation.**

1. SUPPORTING KNOWLEDGE AND/OR SKILLS

a. Describe the effects of radiation exposure on the cellular level including:
   - Direct effects
   - Indirect effects

b. Describe the factors affecting radiation sensitivity of cells (i.e., The Law of Bergonie and Tribondeau).

c. Describe the acute effects and corresponding doses associated with the following:
   - Blood changes
   - Hemopoietic syndrome
   - Gastrointestinal syndrome
   - Central nervous system syndrome

d. Discuss delayed effects of radiation exposure including:
   - Cancer induction
   - Genetic effects
   - Prenatal developmental effects
   - Cataracts

e. Discuss how the Linear Non threshold Theory is used in developing risk estimates and dose limits associated with exposure to radiation. (The use of International Commission on Radiological Protection (ICRP) Publications 26 and 60 or National Council on Radiation Protection and Measurements (NCRP) Report No. 116 may be helpful).

2. SUMMARY

Cells in our bodies are made up of molecules. Molecules are made up of elements that are chemically bonded together in specific ratios and sequences. Electrons are the very nature of chemical bonds and are responsible for holding together elements to form molecules.

Ionizing radiation transfers kinetic energy directly to electrons. If the kinetic energy transferred to the electron exceeds the binding energy that holds the electron in place, the molecular bond can be broken, thus altering the function of the molecule. For this reason ionizing radiation causes biological damage in humans.

The human effects for large acute doses are well known. This data comes from epidemiologic case studies, the largest of which is the atomic bomb survivors. What is somewhat in doubt is the biological effects from low doses of radiation over long periods of time, better known as chronic doses. Although the degree of uncertainty is small for chronic doses, conservative assumptions have been made in setting the radiation protection standards. The result is to establish risk for radiation exposure. Risk can be normalized so that anyone working with radiation does not accept a higher degree of risk than working in any other industry or profession.

Direct and Indirect Effects

Biological radiation effects are classified as either direct or indirect effects. In order to discuss these effects it is necessary to cover the basis of the human cell.

Cells are the building blocks of humans and their living environment. They are the fundamental unit of which all living organisms are made. Although there is no such thing as a typical cell, all cells have several features in common.

Most cells are composed of protoplasm: a mixture of carbohydrates, lipids, proteins, nucleic acids, inorganic salts, gases and between 70 and 80% water. The cell may be subdivided into three major parts:

1. Cell membrane
2. Cytoplasm
3. Nucleu

Cell Membrane

The cell membrane is only 100 angstrom units (100 millionths of a centimeter) thick, and is a living functional part of the cell. It helps to regulate the concentration of water, salts, and organic matter which form the interior environment of the cell. The membrane is thus capable of "active transport." In addition, all food entering the cell and all waste products or secretions leaving it must pass through this membrane.

Cytoplasm

The cytoplasm is a jelly-like substance in which the nucleus is suspended; it is encased within the cell membrane. This material is an aqueous solution of soluble proteins and salts which constitutes the interior environment of the cell.

Nucleus

Each cell contains a small, usually oval, body known as the nucleus. In some cells this has a relatively fixed position and is found near the center; in others it may move around freely and be found almost anywhere in the cell. The nucleus is an important center of control of the cell, directing cellular activity and containing the hereditary factors (genes) responsible for the traits of the animal or plant. The nucleus is the center for cellular reproduction containing deoxyribonucleic acid (DNA).

DNA is the most important material making up the chromosomes and serves as the master blueprint for the cell. It determines what types of ribonucleic acid (RNA) are produced which, in turn, determine the types of protein that are produced. It is generally assumed to take the form of a twisted ladder or double helix. The sides of the ladder are strands of alternating sugar and phosphate groups. Branching off from each sugar group is one of four nitrogenous bases: cytosine, thymine, adenine and guanine. The rungs of the ladder consist of two nitrogenous bases, one from each strand, linked by hydrogen bonds. Cytosine is always paired with guanine and thymine is always paired with adenine. A section of DNA that codes for one protein is referred to a gene although the "message" from several genes can be carried by single piece of RNA.

Chromosomes consist of highly convoluted supercoils of DNA and associated proteins. Each chromosome possesses a single centromere, a short specialized section of the chromosome that serves as a type of attachment point. The centromere must be present for the appropriate movement of the chromosomes during cell division. To ensure its survival, each new cell must possess all the required DNA.

Direct Effect

The complexity and importance of DNA to the survival of the cell make it very radiosensitive. Any changes or alterations to the genetic blueprint can kill the cell or change the genetic code necessary for reproduction. Therefore, the DNA is considered to be a critical target in the cell. Damage to a critical target (primarily the DNA strand) by ionization or excitation is called a direct effect. Ionizations can break the chemical bonds that hold the DNA strand molecules together.

Once a DNA strand has been damaged (i.e., the electronic bond has been broken) there is a 95% probability that the DNA will repair itself normally and continue to function. There is a 5% probability that the DNA will not repair normally and die at the next reproduction phase, called the "mitosis phase," or survive with an incorrect genetic code which could, in theory, cause a cancer at a future date.

Whether the cell survives depends on how many hits the DNA strand takes simultaneously. If the DNA strand takes two simultaneous hits (i.e., ionizing events) called a double strand break, the cell will die. Celluar repair can occur from a single strand break if the cell is given sufficient time to repair before the next radiation interaction. It should be noted that single strand breaks to the DNA occur from other reasons, and the body repairs about 100,000 single strand DNA breaks daily.

Indirect Effect

The DNA strand is rather small compared to the whole cell; therefore, the likelihood of radiation causing ionization or excitation on the DNA strand is small. Since the cell is comprised mostly of water (70 to 80%), it is more likely that the radiation will cause damage or cause changes to water molecules. If the water molecule breaks up (dissociates), some of the parts will be charged. These fragments are called free radicals and are not chemically stable.

Free radicals are electrically neutral structures with one unpaired electron (e-). For example, an excited H_2O^* molecule may dissociate into

$$H_2O^* \rightarrow H^\circ + OH^\circ$$

in which the hydrogen radical H° has an unpaired e^- and the OH° radical will have nine e^-, one of which will be unpaired. The free radicals are very reactive chemically, and when combining can produce hydrogen peroxide (H_2O_2), which is a chemical poison to the cell and is the most harmful free radical product. Hydrogen peroxide is a somewhat stable compound which can survive long enough to diffuse throughout the body, oxidizing molecules or cells which did not suffer from the original radiation

damage. Additionally, H_2O_2 can readily become a peroxide radical with the ability to attack other bio-organic molecules to form stable organic peroxides. For example, if an important cellular enzyme was converted to a peroxide, it would no longer be useable at its phase in the cell cycle resulting in irreparable injury and ultimately cell death. These further effects are known as indirect effects because the by-products of radiation interactions are toxic to the cell, causing cell death or damage.

Cellular Radiosensitivity

It is generally accepted that the DNA strand is the most critical target in the cell, although there may be others. A cell has a life cycle that is divided into four phases called G1, S, G2, and mitosis. Cellular reproduction occurs in the mitosis phase and is called mitosis. Mitosis is a process of reproduction where the DNA strand splits or divides into two exact copies. Of the four phases, mitosis is the most radiosensitive. The reason(s) for this are not clearly understood.

Most cells in the body undergo mitosis at some point, but the rate or life cycle period is different for different types of cells. The higher the rate of mitosis, the greater the radiosensitivity. These differences in sensitivity are stated in the Law of Bergonie and Tribondeau: "The radiosensitivity of a tissue is directly proportional to its reproductive capacity and inversely proportional to its degree of differentiation." In other words, cells most active in reproducing themselves and cells not fully mature will be most harmed by radiation. This law is considered to be a rule-of-thumb, with some cells and tissues showing exceptions.

Since the time that the Law of Bergonie and Tribondeau was formulated, it is generally accepted that cells tend to be radiosensitive if they:

1. Have a high division rate (i.e., cell cycle time, or time between divisions).
2. Have a high metabolic rate.
3. Are of a non-specialized type (i.e. a cell which is capable of specialization into an adult cell type, such as a fertilized ovum).
4. Are well nourished.

Used generally, tissues which are young and rapidly growing are most likely radiosensitive. The law can be used to classify the following tissues as **radiosensitive**:

- Germinal (reproductive) cells of the ovary and testis, i.e., spermatogonia
- Hematopoietic (bloodforming) tissues: red bone marrow, spleen, lymph nodes, thymus
- Epithelium of the skin
- Epithelium of the gastrointestinal tract (interstitial crypt cells)

The law can be used to classify the following tissues as **radioresistant**:

- Bone
- Liver
- Kidney
- Cartilage
- Muscle
- Nervous tissue

Acute Radiation Effects

Introduction

Acute radiation effects occur after receiving an acute dose of radiation, which is considered a large dose in a short period of time (i.e., hours or minutes). Although there is no specific cut off as to what an acute dose is, for biological purposes significant health effects begin to occur above 100 rad received within seconds, minutes, or hours. At high doses and high dose rates the body is not able to repair cellular damage.

Generally, acute radiation doses are reported in rad, which will determine the onset of acute radiation syndromes which will be discussed later in this lesson. The reason rad is used in acute situations is because the quality factors:

- Do not apply to high doses
- Do not apply to high dose rates
- Are relevant to only the "risks" of late effects

Acute effects of radiation will manifest themselves within 60 days of exposure. The higher the dose received, the shorter the latency period for the onset of any syndrome.

Lethal Dose

Radiation effects vary greatly from organism to organism. Not only do organisms vary in their sensitivity to radiation, but individuals of the same species also react differently. Because of this biological variability, the dose which is lethal to 50% of the individuals exposed is used as a bench mark called LD 50/30. LD 50/30 is defined as an acute dose of radiation expected to cause death (lethal dose) within 30 days to 50% of those exposed, without medical treatment. The best estimate for the LD 50/30 for humans is between 300 and 500 rad, and is usually stated as 450 rad.

Radiation Syndromes and Stages in Man

A syndrome is a combination of symptoms resulting from a single cause and occurring together so as to constitute a single clinical picture. While any of the three radiation syndromes can cause death, the dose range for each of the three to cause death varies as does the dose required.

Each syndrome can be considered to progress through the following four stages: the prodromal (initial) stage, the latent phase, a period of illness, and recovery or death.

Prodromal Stage. This is the first set of symptoms that occur following a sufficiently large acute dose. The symptoms may include nausea, vomiting, and diarrhea (NVD), as well as anorexia (loss of appetite), and fatigue. The actual causes of the prodromal symptoms are unknown. To some degree, the time of onset of these symptoms is indicative of the magnitude of the dose; however, the appearance of these symptoms, especially nausea and vomiting, can also be induced psychologically.

Latent Phase. This is an asymptomatic period between the prodromal stage and the onset of symptoms of later stages. The higher the dose, the shorter the latent phase. At sufficiently high doses the latent phase effectively disappears.

Illness. Many of the characteristics of the prodromal stage reoccur along with a variety of additional symptoms, i.e., ulcerations about the mouth, fever, etc.

Recovery or Death. With an acute dose above 1,000 rad death is probably certain, even with the best of medical care. It is generally believed that, without medical attention, death is certain above 600 rad.

Blood Changes

Blood is made up of a number of different types of cells including: white blood cells (WBCs), called leucocytes; red blood cells (RBCs), called erythrocytes; and platelets. White blood cells are responsible for fighting bacterial infections. There are two major types of white blood cells, granulocytes and lymphocytes. Granulocytes make up about 75% of white blood cells, are produced in the bone marrow, and live for about 3 days. Lymphocytes make up the remaining 25% of white blood cells, are produced in the lymph nodes and spleen, and live for about 24 hours.

Lymphocytes are very sensitive to radiation. Laboratory tests show a decrease in lymphocyte counts in the blood after doses as low as 25 rad. However, these results were obtained under sterile conditions with lab animals. Humans in the workplace do not live in sterile conditions and the WBC count varies with the number of stressors the individual has; including, general health, exposure to colds and viruses, and even strenuous exercise. This variation in WBC counts can be 200 to 300% at any given time and a 30 rad exposure may not be observable in a real world situation. In the occupational world the detection of blood changes due to radiation exposure may be around 100 rad.

Hematopoietic Syndrome

The hematopoietic system syndrome is a result of RBCs, WBCs, and platelets being killed by radiation. This effect can begins to be seen in doses around 100 rad in humans. Increasing doses to the 200 to 600 rad range can result in death without medical treatment. The individual initially suffers from nausea and vomiting, appears to recover in about three days, but the blood-forming organs continue to atrophy. In two to three weeks, symptoms again begin to appear; they include chills, fatigue, pinpoint hemorrhages in the skin, and ulceration of the mouth and pharynx. The peak incidence of death in humans is 30 days after exposure, but deaths continue up to 60 days.

The bone marrow is primarily the critical organ. While mature RBCs and WBCs are somewhat resistant to radiation, the immature stem cells, precursors to WBCs and RBCs, are very radiosensitive. After the mature RBCs and WBCs die from natural causes (age) there are no replacement cells. The body becomes depleted in RBCs and WBCs and susceptible to infection. Infection is an important cause of death but may be controlled to a large extent by antibiotic therapy. The LD 50/30 dose can be raised by about factor of two with the use of antibiotics.

Progress of the Hematopoietic System Syndrome

Prodromal Stage. Following a dose of 200 to 1,000 rads the prodromal stage, with its associated nausea, vomiting, and diarrhea (NVD), will occur within one to five days of the exposure.

Latent Phase. This asymptomatic period will last one to three weeks after the prodromal stage.

Illness. Following the latent phase a period of extreme illness begins. Characteristic symptoms of this period include NVD, fatigue, anemia (brought about by the decrease in the RBC population), fever, epilation, anorexia, and petechial (pinpoint) hemorrhaging on the skin caused by damage to the lining of capillaries.

Death or Recovery. Death, if it occurs, will be within two to eight weeks after exposure. The most probable causes of death will be hemorrhaging and infection. The hemorrhaging is caused by damage to the radiosensitive cells lining the fine blood vessels and is compounded by the reduced population of platelets. Infection occurs because the intestinal bacteria penetrate the damaged lining of the gastrointestinal tract. At the same time, the body's ability to fight infection is reduced due to a decrease in the number of WBCs.

Gastrointestinal Tract Syndrome

The gastrointestinal (GI) tract is covered with small finger-like projections called villi. Villi add to the effective surface area of the lining and thereby increase the capacity of the body to absorb nutrients. The cells on the surface of the villi are constantly migrating towards the tip of the projections where they are sloughed off. Mitotically-active cells (crypt cells) at the base of the villi replace those that are lost. The turnover rate of these epithelial cells is high--they have an average life span of one to three days.

Sufficiently large acute exposures lead to the reproductive death of the rapidly dividing crypt cells. The cells covering the villi continue to be sloughed off, but are no longer replaced. This deterioration of the lining of the GI tract then leads to a loss of body fluid, inadequate absorption of nutrients, and infection from the intestinal area.

At doses less than 1,000 rad the crypt cells can recover in about a week. For acute whole-body exposures greater than 1,000 rad the crypt cells will not survive. Surgical replacement of the small intestine is not possible and, therefore, survival is impossible. Death occurs within one to two weeks from both the damage to the lining of the GI tract (resulting in circulatory collapse) and damage to the hematopoietic system. A dose of 1,000 rad represents the maximum survival whole-body dose provided that extensive medical care is given.

Prodromal Stage. Within a couple of hours of the exposure, the individual will demonstrate a sharp loss of appetite, upset stomach, and apathy. Several hours later NVD will occur.

Latent Phase. By the third day after the exposure, the previous symptoms will have disappeared and the victim will appear healthy. The asymptomatic latent phase will last from one to seven days.

Illness. A period of severe illness will follow the latent phase. This will include NVD, fever, apathy, anorexia, and loss of weight.

Death or Recovery. Death, if it occurs, will be within three to twelve days of the exposure. If the cell renewal mechanism of the GI tract has been completely destroyed and cannot be replaced, death is inevitable. The causes of death include fluid and electrolyte losses (*circulatory collapse*) brought about by the destruction of the lining of the GI tract. These fluid losses also account for the loss of weight, diarrhea, and thickening of the blood associated with the GI syndrome. Another contributing cause of death is infection. The latter can occur within 24 hours of the exposure as the bacteria that inhabit the GI tract invade the body across the damaged lining. Damage to the hematopoietic system simultaneously reduces the body's ability to cope with the infection.

Central Nervous System (CNS) Syndrome

The CNS syndrome is produced by acute whole-body exposures above 2,000 rad; exposure of the head alone may have similar effects. Death results from respiratory failure and/or brain edema caused from direct or indirect effects on the CNS.

Although the CNS syndrome is not well understood, it most likely involves a combination of cellular and vascular damage. In other words, there may be direct damage to the brain cells by the radiation and indirect damage mediated by effects on the blood vessels of the brain. The latter are known to be damaged by such doses of radiation. Fluid from the blood is lost through the damaged vessel walls into the skull cavity so the pressure inside the skull builds up. Perhaps pressure on certain areas of the brain, i.e., the respiratory center, may be most important, or it may be the change in the blood supply to the brain.

At these high doses, the individual stages of the CNS syndrome become so short that they cannot be distinguished. Following such exposures, the individual may function coherently for a short while or immediately go into shock. Within hours the symptoms become very severe. Symptoms include vomiting, diarrhea, apathy, disorientation, and tremors. The victim is also likely to fall into a coma. Death will be due to respiratory failure and/or brain edema and occurs within 30 hours.

The hematopoietic and GI syndromes do not have time to fully manifest themselves before death occurs and generally do not play a role in death.

Chronic Radiation Effects

Chronic radiation effects can be classified as:

- Somatic (effects to the exposed individual)
  - Cancer
  - Leukemia
  - Cataracts
- Genetic (effects to the progeny of the exposed individual)
  - Mutations
- Teratogenic (effects to the embryo exposed in utero)
  - Malformations

Somatic Effects

Chronic exposures are considered low doses of radiation over a relatively long period of time (weeks to years). The effects, if any, do not manifest themselves until years after the exposure. Other than radiation sickness associated with acute exposures, there is no unique disease associated with chronic radiation exposure; only a statistical increase exists in the development of harmful effects. The following section discusses possible chronic effects from exposure to ionizing radiation.

Cancer. With proper selection of animal species, strains, and dose, ionizing radiation may be shown to exert an almost universal carcinogenic action resulting in tumors in a great variety of organs and tissues. There is human evidence that radiation may contribute to the induction of various kinds of neoplastic diseases. Human evidence includes radium dial painters, radiologists and dentists, uranium miners, and atomic bomb survivors. The main sites of solid tumors are the breasts in women, thyroid, lung and some digestive organs. These tumors have long latent periods (approximately 10 to greater than 30 years) and occur in larger numbers than leukemia.

Leukemia. Leukemia (abnormal increase in WBCs) was first noted in radiologists who used radiation in their practices. The incidence of leukemia was much greater for radiologists than other physicians who did not use radiation. Also, atomic bomb survivors within 1,500 meters of the blast center showed significantly higher incidence of leukemia than those beyond 1,500 meters.

Leukemia has a much shorter latent period. The incidence of leukemia peaks at three to four years after exposure and returns to normal levels after about 25 years. Leukemia induction is also a function of the type of radiation. In Nagasaki, leukemia induction was not seen in individuals with exposures less than 100 rad; while in Hiroshima, leukemia was seen in doses between 20 to 40 rad. The difference being that Hiroshima had a much greater neutron dose than Nagasaki.

Cataracts. The lens of the eye is highly susceptible to irreversible damage by radiation. When the cells of the lens become damaged, they lose their transparency and a cataract is formed. Exposures around 200 rad may produce a cataract; although, the symptoms and signs may not be apparent for years after the exposure. The damaging effects of penetrating radiation to the lens of the eye may be cumulative and repeated small doses may result in cataract formation.

Radiation induced cataracts are produced primarily by neutron and gamma radiation. Experiments with animals and human case histories indicate that neutron radiation constitutes the greatest danger, with gamma radiation of slightly less importance. It is interesting to note that radiation-induced cataracts differ from naturally occurring cataracts. Radiation induced cataracts form on a different position on the lens of the eye.

Susceptibility to radiation induced cataract formation seems to be somewhat dependent on age. Radiation is more likely to produce cataracts in younger persons, because of continuous growth of the lens (growing tissues are more radiosensitive).

Extensive irradiation of the eye may result in inflammation of the cornea or in an increase in tension within, and hardening of, the eyeball. These conditions usually become manifest several weeks after the exposure and may terminate in loss of vision.

Genetic Effects

Genetic effects are assumed to occur in humans; although, there is no definitive data to substantiate this. Data developed from the atomic bomb survivors leaned in the direction of genetic effects in humans, but the data was not statistically significant. Information on genetic effects are based almost entirely on animal experiments. Experiments with mice have yielded data for radiation induced genetic effects that can be applied to humans with some measure of confidence.

Mutations

The essential characteristics of humans are passed from one generation to the next by means of genes, which are strung together in beadlike fashion to form tiny filaments known as chromosomes. Human body cells normally contain 46 chromosomes, made up of two similar (but not identical) sets of 23 chromosomes each. The 46 chromosomes of a human are believed to contain on the order of 10^4 genes, and it is these genes that, when passed on to the next generation, will determine the physical and psychological characteristics of the individual.

At conception, the set of hereditary characters from the father are united with those from the mother. As the individual develops, the 23 chromosome pairs (one-half from each parent), formed by the union of the egg and sperm, are almost always duplicated without change. In some instances, however, the chromosome will fail to duplicate itself in every respect. This change, called a mutation, is a change in the structure of the DNA which may involve either the base composition, the sequence, or both. An alteration involving the substitution, gain, or loss of a single gene can be the cause of significant inheritable changes. If the mutation occurs in a germ cell (sperm or ovum) or in the tissues of the organ in which the germ cells are produced, no visible injury will be sustained by the individual, but the effect may appear in future generations.

Mutations can be either dominant or recessive. Dominant gene mutations are expressed in the first generation and need to be present in only one parent. Recessive mutations occur in subsequent generations because the mutant gene must be supplied by both parents before being expressed. About 20% of radiation- induced mutations are expressed in the first generation. The other 80% of radiation-induced mutations are expressed in all subsequent generations. It is impossible to determine whether the change occurred naturally or whether it was the result of exposure to radiation.

Radiation does not produce new or unique genetic effects, but increases the frequencies of mutations that already occur spontaneously in nature. About 10% of all live births involve some sort of spontaneous mutation ranging from mild to serious. The reasons for the vast majority of spontaneous mutations are not well understood. But, it is estimated that not more than 1 to 6% of spontaneous mutations in humans may be the result of background radiation. An additional dose of 1 rem per generation results in an increase of the natural or spontaneous mutation rate by about 1%. Based on atomic bomb survivor data, the doubling dose required to double the natural or spontaneous mutation rate is 158 rem. It appears that the radiation- induced mutation has no threshold dose and appears to follows a linear model.

Approximately 99% of all mutations are considered to be undesirable. Genetic damage in humans can result in a decrease in life expectancy, inability to produce offspring, an increased susceptibility to disease, or any number of changes of lesser or greater importance.

Teratogenic Effects

The Law of Bergonie and Tribondeau indicates that the radiosensitivity of tissue is directly proportional to its reproductive capacity and inversely proportional to the degree of differentiation. It follows that children could be expected to be more radiosensitive than adults, fetuses more radiosensitive than children, and embryos even more radiosensitive.

Most of the data involving teratogenic effects comes from the atomic bomb survivors, which shows evidence of both small head size and mental retardation. Most children in the study received doses ranging from 1 - 50 rad. For a radiation dose of 1,000 mrem at four to seven weeks after conception, the excess cases of small head size was five per thousand, at eight to eleven weeks, it was nine per thousand. There were no cases of mental retardation in children exposed from zero to eight weeks after conception. Starting at eight weeks after conception, the incidence of mental retardation increases at a linear rate with increasing dose. The dose to the fetus, which causes mental retardation in 40% of exposed fetuses, is approximately 100 rad. The age at which the fetus was exposed was a critical factor in determining the type of effect and the risk.

The effect on the unborn child depends on the stage of fetal development. There are three stages to fetal development:

- Preimplantation
- Organogenesis
- Fetal

The preimplantation stage in humans is a period of zero to nine days after conception. This period extends from fertilization of the egg to the point the embryo attaches to the wall of the uterus. This is the most sensitive stage for lethal radiation effects. High doses on the order of 200 rad will generally result in prenatal death. If the fetus survives radiation exposure during this period, it will generally grow normally afterwards with few congenital abnormalities.

The organogenesis stage in humans is a period of ten days to six weeks after conception when the major organs are developed. Any radiation induced malformations usually involve the CNS. Radiation-induced malformations of body structures other than the CNS are uncommon in humans, but significant growth retardation can occur during this period. Death of the fetus from radiation overexposure is likely to be at or near birth.

The fetal stage is a growth period for already formed structures and in humans begins six weeks after conception. Radiation effects observed in atomic bomb survivors include small head size and mental retardation. The peak risk period for mental retardation occurs eight to fifteen weeks after conception.

Development of Risk

Ideally, in order to develop standards for exposure to any harmful agent, risk factors must be calculated and compared to a standard risk or acceptable risk. The development of risk requires human epidemiological data from a reliable control group(s) exposed to known doses of radiation. It also requires scientists with the proper training and skills to evaluate the epidemiological data and the financial resources to conduct research. In the early 1900s such technical skills did not exist, they were developed over the years as the scientific knowledge of radiation biology accumulated. These factors have led to a long learning curve to establish scientifically credible radiation protection limits that have only recently been instituted. A brief overview of the history of risk based limits follows.

Soon after the discovery of radiation, the harmful effects of radiation in humans became apparent as doctors and technicians working with radiation developed skin cancers. The early limits were based on the concept of tolerance doses, which were observed effects that had a threshold value. At the time, the threshold effect that was well documented was a reddening of the skin called erythema.

The first radiation protection limits were set at 5 roentgen (R) per month or 0.2 R per day. These values would prevent erythema and it was reasoned that the body could repair itself to prevent any damage. These limits stood until 1936, when the recently established Advisory Committee on X-ray and Radium Protection reduced the limit to 0.1 R per day.

The reduction was not based on hard scientific evidence, but rather on a general feeling the limit should be reduced. Studies showed that blood cell counts of technicians working with radium did not change when receiving average daily doses of 0.1 R, also, genetic hazards were beginning to become apparent. Based on this information, which was the best at the time, the radiation limit was reduced.

In 1949, the newly established NCRP recommended that the limit be reduced to 0.3 rem per week. This reduction was not based on any scientific evidence, just a desire to be safe.

In 1956, with the emergence of nuclear power, the need for more comprehensive limits became apparent. There was a shift in radiation protection away from preventing acute effects to limiting chronic effects to acceptable levels. Specifically, the genetic effects on humans posed a concern to the NCRP and they lowered the limit by a factor of three to 0.1 rem per week.

In 1977, the ICRP revised its recommendations in ICRP 26/30 based on data that had become available over the previous decade. Large bodies of information were gathered and analyzed. Some of the larger sources of information came from the following sources:

- Radium dial painters
- Radiologists and dentists
- Uranium miners
- Atomic bomb survivors
- Ankylosing spondylitis patients
- Children irradiated for thymus enlargement
- Patients treated by pneumothorax
- Children of mothers irradiated during pregnancy

In evaluating the epidemiological data, it became apparent that radiation had different types of effects. Some effects were observable soon after a large acute dose and had specific threshold doses, such as erythema. Other types of effects manifested themselves many years after exposure and did not have a specific threshold dose, such as cancer. As a result of these observations, the ICRP 26/30 classified radiation effects as either stochastic or nonstochastic.

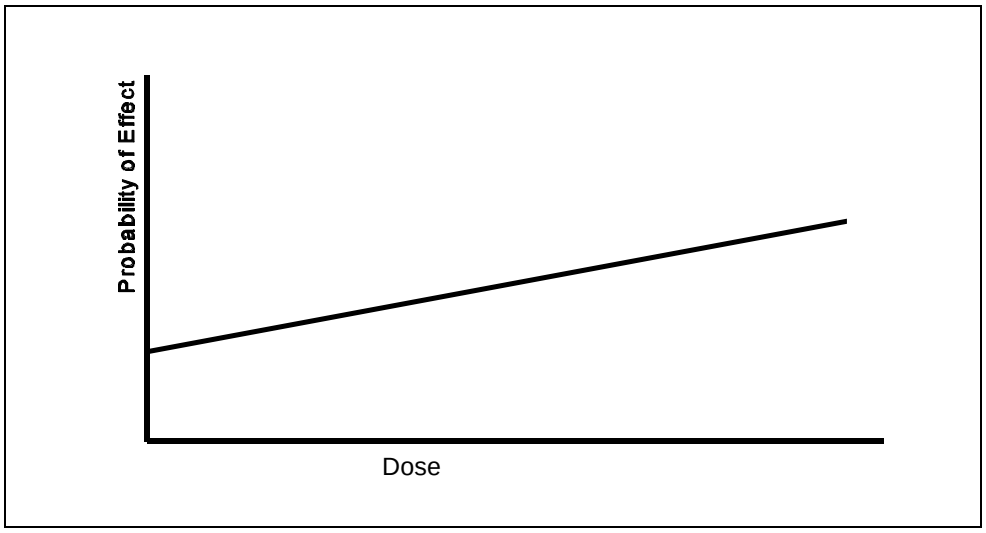
Stochastic effects are defined as: malignant and hereditary diseases for which the probability of an effect occurring increases continuously with increasing absorbed dose while the severity of the effect, in the effected individuals, is independent of the magnitude of the absorbed dose.

Nonstochastic effects (also called deterministic effects in ICRP 60/61) are defined as: effects due to radiation exposure for which the severity varies with the dose and for which a threshold normally exists (e.g., radiation-induced opacities within the lens of the eye).

In ICRP 26/30, the premise of radiation protection is to limit stochastic effects to an acceptable level of risk and prevent nonstochastic effects from occurring. This goal is met by limiting stochastic exposures to 5 rem per year and nonstochastic exposures to 50 rem per year.

In order to calculate risk, models were developed that would characterize the induction of harmful radiation effects as a function of dose. As the model was refined, it became harder and harder to establish a well-defined relationship between chronic doses and harmful effects. Because of this, the threshold theory was replaced by the nonthreshold theory which holds that any exposure, no matter how little, has some effect on the body. Figure 8 shows this theory as it was originally proposed, in terms of a linear relationship. *Health Effects of Exposure to Low Levels of Ionizing Radiation* (BEIR V report) endorses this model for "hard" cancers.

Figure 8
Linear Nonthreshold Theory



In developing the threshold model, the data points were based on sources of epidemiological data given earlier. The doses that individuals received were from high doses, well above occupational limits, and very high dose rates. There was very little data available at low doses or dose rates in sufficient numbers to develop meaningful conclusions on risk. In light of the absence of data at low doses and dose rates, available data was graphed and extrapolated backwards using a linear model suggested by BEIR V.

The numerical risk factors calculated from the linear model are 8×10^{-4} per rem of exposure. Studies have shown that the biological effect, or risk, is greater at higher doses and dose rates by a factor of 2 to 2.5. A dose rate reduction factor (DRRF) of two was applied to the linear model risk factor to calculate the occupational risk factor of 4×10^{-4} per rem of exposure to more accurately reflect the occupational risk. It is the desire of the NCRP to set the risks of radiation exposure comparable to other safe industries. According to the National Safety Council, which tracks accident statistics in all industries, the risk of death in safe industries is 1×10^{-4}, or less, per year. Receiving an occupational dose of one rem per year for 30 years is about the average risk for safe industries.

Although the federal limit of 5 rem per year is considered safe, there is a numerical level of risk involved with the term safe no matter what the hazardous agent is. The linear model suggests that some dose, no matter how small, carries some risk. This serves as the basis for the As Low As Reasonably Achievable (ALARA) philosophy that has evolved in radiation protection over the years. By reducing your dose as far below the limits as is possible, your corresponding risk is also lowered.

3. SELF STUDY SCENARIOS/ACTIVITIES AND SOLUTIONS

Review

- 10 CFR 835, *Occupational Radiation Protection.*
- DOE N 441.1, *Radiological Protection for DOE Activities.*
- DOE/EH-0256T (Revision 1), *Radiological Control Manual*.
- DOE Order 5480.4, *Environmental Protection, Safety, and Health Protection Standards.*
- G-10 CFR 835, Revision 1, *Implementation Guides for Use with Title 10 Code of Federal Regulations 835.*
- Cember, Herman (1996). *Introduction to Health Physics*.
- Gollnick, Daniel A. (1991). *Basic Radiation Protection Technology*.
- Argonne National Laboratory. (1988). *Department of Energy Operational Health Physics Training*.
- National Research Council, National Academy Press. (1990). *Health Effects of Exposure to Low Levels of Ionizing Radiation (*BEIR V Report). Washington, DC: Author.

Scenario

A worker at a DOE contractor facility is using an x-ray diffraction device to perform crystal-structure analysis in materials research. During a sample change, one of the worker's hands is inadvertently exposed to the primary beam.

1. What is the major hazard from this particular x-ray generating device?

2. What potential exposures and biological effects could result?

Scenario, Solution

1. The major hazard associated with x-ray diffraction units is the intense, localized exposure from the primary beam to the hands or the eyes that can occur during a change of samples or beam alignment. This scenario involves a situation where the sample could not be enclosed in a protective structure and a "shutter" was left open, exposing one of the worker's hands. (**NOTE:** This cannot occur in many of the new, interlocked units.)

2. The primary beam is very small, but can result in intense fields on the order of several hundred thousand roentgen per minute (R/min). These exposure rates can produce severe dermatological injury and potential loss of fingers.

4. SUGGESTED ADDITIONAL READINGS AND/OR COURSES

Readings

- Argonne National Laboratory. (1988). *Department of Energy Operational Health Physics Training* (ANL-88-26). Argonne, IL: Author.
- Cember, Herman (1996). *Introduction to Health Physics* (3rd ed.). McGraw-Hill: New York.
- Gollnick, Daniel A. (1991). *Basic Radiation Protection Technology* (2nd ed.). Pacific Radiation Corporation: Altadena, CA.
- International Commission on Radiological Protection. (1977). *Recommendations of the International Commission on Radiological Protection* (ICRP 26). New York: Author.
- International Commission on Radiological Protection. (1991). *Recommendations of the International Commission on Radiological Protection* (ICRP 60). New York: Author.
- National Council on Radiation Protection and Measurements. (1993). *Limitation of Exposure to Ionizing Radiation* (NCRP Report No. 116). Bethesda, MD: Author.
- National Research Council, National Academy Press. (1990). *Health Effects of Exposure to Low Levels of Ionizing Radiation* (BEIR V Report). Washington, DC: Author.
- United Nations Scientific Committee on the Effects of Atomic Radiation. (1988). *Sources, Effects, and Risks of Ionizing Radiation* (UNSCEAR 1988 Report to the General Assembly). New York: Author.
- U.S. Environmental Protection Agency. (1987). *Radiation Protection Guidance to Federal Agencies for Occupational Exposure* (52 FR 2822). Washington, DC: Author.
- U.S. Environmental Protection Agency. (1988). *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion*, Federal Guidance Report No. 11 (EPA 520/1-88-020). Washington, DC and Oak Ridge, TN: Author.

Courses

- *Nuclear Physics/Radiation Monitoring* -- DOE.
- DOE/EH-0450 (Revision 0), *Radiological Assessors Training (for Auditors and Inspectors) - Fundamental Radiological Control,* sponsored by the Office of Defense Programs, DOE.
- DOE/EH-0450 (Revision 0), *Radiological Assessors Training (for Auditors and Inspectors) - Applied Radiological Control,* sponsored by the Office of Defense Programs, DOE.
- *Applied Health Physics* -- Oak Ridge Institute for Science and Education.
- *Radiation Protection Functional Area Qualification Standard Training* -- GTS Duratek.

Other

Actions or situations were combined to create new incidents from the following references:

- DOE/EH-0450 (Revision 0), *Radiological Assessors Training (for Auditors and Inspectors) - Applied Radiological Control, Lesson 12-I (Radiation-Generating Devices).* {**NOTE**: This reference is from a course sponsored by Defense Programs at the DOE.}
- U.S. Department of Energy. (1996). *Operating Experience Weekly Summary. (96-17,* April 19 through 25, 1996. Final Report Number 1.). Washington, DC, Office of Nuclear and Facility Safety.